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HUMAN FACTORS ANALYSIS OF U.S. NAVY AFLOAT MISHAPS

by

Rex D. Lacy

September 1998

Thesis Advisor:
Second Reader:

Samuel E. Buttrey
John K. Schmidt

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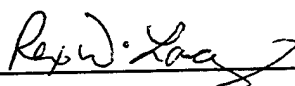
Rex D. Lacy
Lieutenant Commander, United States Navy
B.S., Georgia Institute of Technology, 1982
M.S., Central Michigan University, 1998


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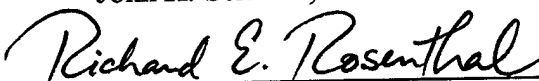
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Author: 
Rex D. Lacy

Approved by: 
Samuel E. Buttrey, Thesis Advisor


John K. Schmidt, Second Reader


Richard E. Rosenthal, Chairman
Department of Operations Research

ABSTRACT

The effects of maritime mishaps, which include loss of life as well as environmental and economic considerations, are significant. It has been estimated that over 80 percent of maritime accidents are at least partially attributable to human error. Human error has been extensively studied in a number of fields, particularly aviation. The present research involves application of the Human Factors Accident Classification System (HFACS), developed by the Naval Safety Center, to human error causal factors identified in selected investigation reports of significant mishaps occurring on U.S. Navy afloat and diving units from 1992 to 1996. An evaluation of the reliability of the classification system was performed by measuring the level of agreement between two independent raters' application of the system to mishap analysis. Descriptive statistics and categorical data analysis were performed and meaningful insights were revealed regarding the types of human error that were associated with afloat naval mishaps. Comments and recommendations regarding implementation of the classification system for use in maritime accident analysis are provided.

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EXECUTIVE SUMMARY

The effects of maritime mishaps, which include loss of life as well as environmental and economic considerations, are significant. It is estimated that over 80 percent of maritime accidents are at least partially attributable to human error. Human error has been extensively studied in a number of fields, particularly aviation. The present research involves evaluation of a taxonomy, called the Human Factors Accident Classification System (HFACS), for applicability, reliability, and usefulness in the post hoc analysis of mishap investigation reports of 46 significant mishaps (i.e., involving a fatality, permanent disability, or equipment damage exceeding \$1 million) that occurred on U.S. Navy ships and submarines between 1992 and 1996. HFACS was developed by personnel at the Naval Safety Center in Norfolk, Virginia, as an application of existing human error theories to accident investigation and analysis. This system had already been adopted by the U.S. Navy and Marine Corps for use in aviation mishap investigation and analysis.

The research determined that the taxonomy supported classification of over 90 percent of 496 causal factors cited in the reports. The remaining causal factors involved material and environmental issues. The reliability of the taxonomy for use in ship and submarine mishap analysis was evaluated by comparing the level of agreement between two judges with equivalent understanding of HFACS as they independently classified the mishaps per the taxonomy. Agreement between the two judges was determined to be good.

Differences in causal factor classification between the judges were resolved by consensus and the resulting classifications were used for subsequent exploratory data analysis. This analysis consisted of sorting the data by mishap types (fatality, collision/grounding, or other equipment damage) and ship type (carrier, combatant, auxiliary, amphibious, and other). Fatal mishaps were further sorted by type (general, diving, maintenance, or man-overboard). Each mishap had instances of the different error types, and the percentages of mishaps with each of the error types were determined. A significant difference was found between the types of errors cited in mishaps involving fatalities and those involving equipment damage only. Conversely, differences between mishap causal factors types with respect to mishap unit fleet origin, physical location (i.e., at sea or in port), and mishap time of day were not found to be significant.

The research concluded that HFACS was indeed useful in the analysis of ship and submarine mishaps and the information provided by the application of HFACS for mishap causal factor classification should support development of improved mishap prevention strategies. Recommendations for improving the reliability of classifications include providing more training regarding the taxonomy to personnel applying HFACS to mishap analysis, changing the applicable mishap reporting instructions and directives to reflect the concepts of the human error taxonomy, and encouraging investigating boards to more clearly address the human error issues in their reporting of mishap causal factors. Additionally, the application of HFACS in the analysis of high-interest mishaps, including electrical shock, back injury, and toxic substance exposure, should be aggressively pursued.

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I. INTRODUCTION

A. OVERVIEW

The effects of maritime mishaps, which include loss of life as well as environmental and economic considerations, are significant. It has been estimated that over 80 percent of the mishaps were at least partially attributable to human error (Perrow, 1984). The story of the *Titanic*, in which the ship collided with an iceberg and subsequently sank with nearly 1500 passengers drowned, is a classic case study in human error (Ibid.). One notable fact concerning this disaster is that the captain was overconfident in the ship's seaworthiness and carelessly sailed at night into frigid waters and through a field of icebergs. The active failure of the captain's decision-making was compounded by two latent conditions. The designers thought that no more than three compartments could ever be damaged at once; however, five were torn open during the collision. Additionally, the threat of sinking was so underestimated that lifeboat space was provided for fewer than half the passengers. The ship's capacity was an estimated 2,200 people but it had, incredibly, only 16 wooden lifeboats designed to carry 65 people each, and an additional four, smaller, canvas-sided lifeboats.

As an another example, most people in the United States today are probably familiar with the 1989 grounding of the supertanker *Exxon Valdez* onto Bligh Reef in southern Alaska's Prince William Sound (Wittelman, 1990). This mishap resulted in the spilling of 11.2 million gallons of crude oil into the sea with a considerable cost to local wildlife and environment. The active failure was determined to be that the ship did not promptly return to its assigned transit channel following a routine ice-avoidance

maneuver. The highly publicized investigation speculated that the ship's captain was intoxicated at the time of the accident, a latent condition that set the stage for the active failure that caused the mishap.

Human error has been extensively studied in many contexts, with perhaps the largest area being aviation. Generally described as "pilot error," human error contributing to aviation accidents has been the primary focus of much research by military and civilian organizations (O'Hare, Wiggins, Batt, & Morrison, 1994; Shappell & Wiegmann, 1997a,b). Considerable human error research has also been conducted in other areas of transportation, including highway accidents (Brown, 1990; Fuller, 1990; Lourens, 1990; Malaterre, 1990; Parker, Reason, Manstead & Stradling, 1995). In all these studies, many methodologies for describing and classifying/partitioning the observed human errors have been proposed and used to analyze the accidents.

In 1974, the National Research Council (NRC), the research arm of the National Academy of Sciences (NAS), commissioned a study on "Human Error in Merchant Marine Safety." Their study involved interviews and a questionnaire of over 500 seagoing personnel in an effort to determine the underlying causes of casualties resulting from human error in the U.S. merchant marine (NAS Maritime Transportation Research Board Commission (MTRB) on Sociotechnical Systems, 1976). They concluded that the tolerances for human error had decreased significantly with the introduction of large, fast, and highly sophisticated ships and that the consequences of human error had become greater. The commission also noted that though the chances and consequences of casualties had increased dramatically, the means for countering human error in vessel operations had not kept pace.

The MTRB Commission further identified 14 factors that were either major or potential causes of casualties or near-casualties (NAS MTRB Commission on Sociotechnical Systems, 1976):

1. Inattention
2. Ambiguous pilot-master relationship
3. Inefficient bridge design
4. Poor operational procedures
5. Poor physical fitness
6. Poor eyesight
7. Excessive fatigue
8. Excessive alcohol use
9. Excessive personnel turnover
10. High level of calculated risk
11. Inadequate lights and markers
12. Misuse of radar
13. Uncertain use of sound signals
14. Inadequacies of prescribed navigation rules

The Commission's recommendations addressed each of these factors, and each was directed at the government agency considered most appropriate for the action required -- the Maritime Administration or the U.S. Coast Guard. They also determined that the merchant marine casualty database maintained by the U.S. Coast Guard and other agencies was inadequate for casualty analysis. The impact of this effort could not be determined.

As recently as 1996, the NRC Commission on Human Performance, Organizational Systems, and Maritime Safety held a symposium to examine the issues of maritime safety. The Commission had safety experts from the aviation, nuclear power, and petrochemical industries, the National Transportation Safety Board, and the Federal Aviation Administration, among others, discuss safety practices and interventions used to combat human error in their areas. It was clear from the meeting that many of the processes currently used in other industries would fit in combating maritime human factors problems (J. K. Schmidt, personal communication, April 28, 1998).

B. BACKGROUND

The Naval Safety Center, which is located at the Norfolk Naval Air Station, Virginia, has three directorates: aviation, afloat, and shore safety, and five support departments. Each directorate works independently to help the Chief of Naval Operations and the Commandant of the Marine Corps prevent operational mishaps, promote safety, and monitor safety programs. The Naval Safety Center (NSC) staff collects, evaluates and distributes information about operational and occupational mishaps. The command maintains a computerized repository for reports about injuries, occupational illness and property damage, and publishes statistical data from those reports. Other staff members assist directly or indirectly in investigations into hazards and mishaps; the goal is to recommend policies that will prevent similar mishaps and control known hazards. Naval Safety Center personnel also conduct safety inspections and surveys at operational commands to evaluate the commands' safety programs and practices and make recommendations for improvements (Naval Safety Center, 1997a).

Over the last three years, personnel in the Naval Safety Center's Aviation Safety Programs Directorate have adopted and developed a mishap causal factor coding system to examine human error patterns in aviation-related mishaps. The current version of the human error taxonomy is called the Human Factors Accident Classification System (HFACS). To date, this analytic effort has been primarily limited to Class A flight mishaps attributed to aircrew error. The current effort has revealed that the classification model works well to describe the human error causal factors, and it is anticipated that the mishap prevention strategies based on these analyses will lead to reductions in the frequency of these types of mishaps. Plans currently exist to extend the analysis to maintenance-related mishaps and aviation mishaps of less severity and different classifications, as well as those in other operational communities (J. K. Schmidt, personal communication, March 9, 1998).

C. OBJECTIVE STATEMENT

The purpose of this study is to evaluate the HFACS taxonomy's ability to support the human error analysis of naval afloat mishaps (i.e., those involving ships and submarines). The objective is to use this model to support the development of intervention strategies which may reduce the frequency of future mishaps.

D. PROBLEM STATEMENT

Declining defense budgets and reductions in force structure are proving to be the hallmark of the 1990s for the U.S. military. In many service units, operating tempo has not diminished commensurate with the shrinking force size, and many of these units are often required to do "more with less." The combat readiness of the U.S. military has

become a highly politicized issue and military leaders must give careful consideration to the maintenance of the readiness and numbers of military forces (Spence, 1997).

One requirement for combat readiness is to keep the equipment in good operating condition and minimize the occurrence, duration, and cost of repairs of damage caused by safety mishaps. The Navy unnecessarily spends millions of dollars each year as a result of accidental damage, fatalities, and injuries (Naval Safety Center, 1997b). In 1996, the estimated cost of damages to the government from mishaps involving surface ships and submarines was almost \$28.8 million. These mishaps included five fatalities and permanent disabilities, and the cost does not include lost work days or the cost of medical treatment. Mishaps seriously degrade operational readiness and waste tax dollars. Mishap prevention depends on hazard identification, elimination, control, and correction. The Navy, therefore, has a significant interest in developing tools to further the mishap prevention effort.

Personnel limitations at the Naval Safety Center have prevented aggregated analysis of data relating to significant mishaps on afloat navy units. Analysis and recommendations resulting from investigations of these mishaps have typically been reactive in approach and, though the vast majority of causal factors identified were attributed to human error, no systematic analysis based on contemporary theories of human error has been conducted (J. Sokolowski, personal communication, November 18, 1997).

Given the need to address afloat mishaps in a systematic fashion, an effective adaptation of HFACS must be undertaken. This thesis research will investigate the following issues: (1) Whether the current HFACS taxonomy is applicable to the analysis

of afloat mishaps; (2) Whether HFACS is a reliable method for classifying and analyzing afloat mishaps; and (3) Whether the classification of afloat mishap causal factors using HFACS provides useful information and insights for understanding the mishap causes.

E. SCOPE AND LIMITATIONS

Due to the limited availability of mishap data suitable for human error analysis, only Class A afloat mishap investigation board (MIB) reports from 1992 through 1996 will be examined. MIBs are typically not convened to investigate mishaps in which either suicide or equipment failure not attributable to human error was clearly evident as the primary cause; therefore, Class A mishaps of this nature are not included in the analysis. The remaining research database consisted of 46 mishap reports.

II. LITERATURE REVIEW

A. OVERVIEW

The review of literature for this research included published textbooks covering the subjects of human factors, safety and accident prevention. Topics investigated encompassed human error, maritime safety, maritime accidents, accident analysis, and accident prevention.

B. HUMAN ERROR

1. Definition

Stramler (1993) defined human error as:

An inappropriate response by a system, whether of commission, omission, inadequacy or timing; any discrepancy between an observed or calculated value, and the expected value, or a value known to be correct. (p. 104)

Senders and Moray (1991) described error as "any significant deviation from expectation, depending on statistical criteria or experience of normal performance standards," and human error is distinguished as a "deviation from expected human performance" (pp. 20-21). Reason (1990) provided a working definition for error:

Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency. (p. 9)

Reason's definition will serve as the working definition of human error for the remainder of this analysis.

2. Causes of Human Error

Understanding the causes of human error is a logical first step in any effort to reduce their occurrence; however, cause is a very elusive concept. Heinrich, Peterson

and Roos (1980) contended that errors resulting in accidents could often be attributed to negative character traits of the individual which were either inherited or acquired as a result of the social environment. Through his study of over 75,000 industrial accident reports, he developed ten statements he called *Axioms of Industrial Safety* that he said should be considered by those who wish to prevent accidents. Goetsch (1996) paraphrased the axioms as follows:

1. Injuries result from completed series of factors, one of which is the accident itself.
2. An accident can only occur as the result of an unsafe act by a person and/or a physical or mechanical hazard.
3. Most accidents are the result of unsafe behavior of people.
4. An unsafe act by a person or an unsafe condition does not always immediately result in an accident/injury.
5. The reason that people commit unsafe acts can serve as helpful guides in selecting corrective actions.
6. The severity of an accident is largely fortuitous and the accident that caused it is largely preventable.
7. The best accident prevention techniques are analogous with the best quality and productivity techniques.
8. Management should assume responsibility for safety since it is in the best position to get results.
9. The supervisor is the key person in the prevention of industrial accidents.
10. In addition to the direct costs of an accident (i.e., compensation, liability claims, medical costs, and hospital expenses) there are also hidden or indirect costs. (p. 34)

Assuming that the person responsible for an unsafe act did not intend to be unsafe, then the need to identify the cause for the behavioral error is critical for prevention.

Heinrich et al. (1980) established the idea that accidents cannot be attributed to a single cause. Additionally, errors must be distinguished from accidents, which may be thought of as a manifestation or possible result of one or more errors. An error can have a multitude of causes, and they can be related with one another in a variety of causal

chains. Senders and Moray (1991) stated that what is deemed to be the cause of an accident or error can depend on the purpose of the investigation, with no real, *absolute* cause.

More contemporary theories of human error consider the causes of human error to be the result of a mismatch between the system demands on human performance and actual human capability (Rasmussen, 1987a). Many errors that people commit in operating systems result from bad design or bad organizational structure rather than irresponsible action (Norman, 1988; Reason, 1990; Wickens, 1991). Perrow (1984) described the idea that although human error in accident analyses may be statistically defined as a contributing factor to an accident, the error itself is only one item in a complex chain of breakdowns, some of them mechanical, that affected the system and weakened its defenses.

3. Classifying and Understanding Human Error

There are several theoretical models of error, each of which takes a different perspective on classifying errors. Swain and Guttman (1983) used what they call a simple discrete-action classification model consisting of four categories: *Errors of commission, omission, sequence, and timing*. Errors of commission involve performing an act incorrectly. Errors of omission involve failure to do something. A sequence error occurs when an individual performs some task, or step in a task, out of sequence. A timing error occurs when an individual fails to perform an action within an allotted time, performing either too fast or too slow.

Norman and Lewis (1986) proposed dividing errors into two categories: *mistakes* and *slips*, which are distinguished by level of intention. A person establishes an intention

to act, and if the intention is not appropriate, the error is classified as a mistake. If the person's action is not what was intended, the error is classified as a slip. They acknowledge that it is possible for both to occur simultaneously. Whereas the previous model involved task classification, this model addressed operator intentions.

Rasmussen (1987b) described error types in terms of psychological mechanisms that are being employed by an individual when an error is committed. He identified three levels of cognitive control related to decreasing familiarity with a situational environment: *skill*-, *rule*-, and *knowledge*-based behavior. Skill-based behavior represents sensory-motor performance during an act or activity which takes place without conscious control in a smooth, automated manner once the decision to act is made. Rule-based behavior is characterized as the combination of a sequence of actions in a familiar work situation that is controlled by a stored rule or procedure that the individual previously learned to be useful in the currently perceived situation. At the lowest level of situational familiarity is knowledge-based behavior, where no know-how or rules are known that apply to a situation, forcing an individual to analyze the environment and devise an appropriate response. This approach steps beyond operator intentions and deals with levels of cognitive processing.

Nagel (1988) suggested that most of the possible causes of human error in the airline cockpit could be described by a three-stage information-processing model of human performance. These stages were labeled: (1) *information*, involving acquiring, exchanging, communicating and processing that information; (2) *decision*, involving considering of alternatives and planning a course of action; and (3) *action*, involving

executing of the chosen plan. Both Nagel and Rasmussen were concerned with the stage of cognitive processing at the time of error occurrence.

Wickens and Flach (1988) described another information processing model for representing human error. An individual is confronted with a stimulus and either correctly or incorrectly interprets the stimulus, then develops either a correct or incorrect plan of action, and finally, either correctly or incorrectly execute the plan. They classified errors of interpretation or choice of plan as *mistakes*. Executing the incorrect action with a correct plan, or *vice versa*, is classified as a *slip*. Their model is similar to Nagel's model, but adds Norman and Lewis' concepts of slips and mistakes.

Reason (1990) developed a model of unsafe acts that classified errors according to whether or not the act underlying the decision process was unintentional or intentional. In his scheme, unintentional acts are comprised of two error types: *slips* and *lapses*. Slips are errors resulting from attention failures. An example would be driver who mistakenly signals to turn left when a right signal is intended. Lapses are errors resulting from memory failures. An example would be a driver who forgets to signal at all when initiating a turn.

Intentional acts consist of two more error types called mistakes and violations. Mistakes are classified as either rule-based or knowledge-based. Rule-based mistakes result from the application of a previously learned rule that was either misapplied or was inappropriately learned. Knowledge-based mistakes can occur when an individual is confronted with a situation for which they have no previously learned rule to refer to and the response they derive analytically is inappropriate. Violations, though not strictly an error type, represent unsafe behavior demonstrated by willful disregard of rules and

regulations. Violations can lead to errors and are broken down into two types. Routine violations are those that are typically tolerated by an organization, whereas exceptional violations are significant deviations from acceptable practice (Reason, 1990). A person driving ten miles per hour over the speed limit may be committing a routine violation. A person driving 60 miles per hour over the speed limit, however, is likely committing an exceptional violation.

Reason (1995) later proposed a theory of accident causation that described how human failures, latent or active, contribute to system breakdowns. Latent failures can occur within the upper levels of an organization or at the immediate human-system interface and are created by people who are often remote in both time and space from the hazards. Active failures, in contrast, are committed by those at the immediate human-system interface and hazard environment. His model described two interrelated causal sequences: (a) an active failure pathway that originates in top-level decisions and proceeds via error-producing and violation-promoting conditions in the various workplaces to unsafe acts committed by those at the immediate human-system interface, and (b) a latent failure pathway that runs directly from the organizational processes to deficiencies in the system defenses.

Shappell and Wiegmann (1997a), using the models of human error by Rasmussen, Wickens and Flach and Reason, analyzed Naval aviation mishaps. Their objective was to examine the utility of these different theoretical frameworks for analyzing aviation accidents and to determine if this provided additional insight into the types of error associated with the aviation mishaps. Their success led them devise a new classification system for human error in aviation mishaps: the Taxonomy of Unsafe Operations

(Shappell & Wiegmann, 1997b). The most recent version of the taxonomy was renamed as the Human Factors Accident Classification System (HFACS).

HFACS describes three levels of failure within the human component of Reason's (1990) human error model: (1) unsafe supervision; (2) unsafe conditions of the operator; and (3) unsafe acts committed by the operator. HFACS (Shappell & Wiegmann, 1997b) focuses on failures committed by supervisors as they relate to the psychological and physical condition of the aircrew (latent failures) and ultimately the unsafe acts the aircrews commit (active failures). The objective of the system is to identify failures within each level that have caused mishaps in the past and attempt to prevent their future occurrence. The following paragraphs provide a summary of the HFACS categories (Shappell & Wiegmann, 1998).

Unsafe supervision refers to supervisory acts that either directly or indirectly contributed to a mishap, and consists of *unforeseen unsafe supervision* and *known unsafe supervision* (Reason, 1990). Unforeseen unsafe supervision describes unsafe management or supervisory practices that go unnoticed and are not the result of negligence or adverse behavior. Subcategories of unforeseen unsafe supervision include: (1) unrecognized hazardous operation; (2) inadequate documentation; and (3) inadequate design. An example of an unrecognized hazardous operation would be assignment of a person who just experienced a death in the family to a potentially hazardous task. Inadequate documentation and design refer to documents or designs, specified by or the responsibility of management at a higher organizational level than the affected command, which contributed to the mishap occurrence.

Known unsafe supervision describes failures within the supervisory chain of command that is the direct result of some action or inaction. Subcategories of known unsafe supervision include: (1) inadequate supervision; (2) planned inappropriate operations; (3) failure to correct known problems; and (4) supervisory violations. Inadequate supervision accounts for instances where supervision proves to be inappropriate or absent. Planned inappropriate operations involves instances where improper personnel scheduling and operational planning puts operators at unacceptable risk due to the adverse impact on crew rest and crew pairings. Failure to correct known problems refers to instances where deficiencies among individuals, equipment, training, or other safety-related area are known by the supervisor yet continue to go uncorrected. Supervisory violations are those instances in which supervisors willfully disregard rules and regulations when managing assets.

Unsafe conditions of the operator can contribute to or cause unsafe acts (Reason, 1990), and is further broken down into the categories *medical conditions of the operator*, *crew resource management*, and *personnel readiness*. Medical conditions consist of three subcategories. *Adverse physiological states* account for those medical or physiological conditions that affect safe operation. *Adverse mental state* refers to psychological or mental conditions that negatively impact performance. *Physical or mental limitation* addresses instances when necessary sensory information is not available, or operators do not have adequate ability or time to solve a problem. *Crew resource management* refers to poor coordination and communication between operators or watch-teams. *Readiness violations* refer to violations of rules that adversely impact personnel performance.

The final major category of HFACS, unsafe acts of the operator, consists of *errors* and *violations* and are derived largely from Reason's (1990) work. Errors are defined as mental or physical activities that fail to achieve their intended outcome. There are three basic error types: *perceptual errors*, *skill-based errors*, and *decision errors*. Perceptual errors occur when a situation is misrecognized or the operator's perception is not consistent with reality. Skill-based errors are errors in the execution of a response that has become highly automated. This type of error includes slips or lapses. Decision errors describe situations where intentional behavior proceeds as intended, yet the chosen plan or goal proves inadequate to achieve the desired outcome. Decision errors may contain either rule-based or knowledge-based errors, as previously described in the section on human error classification. Violations committed by the operator consist of *infractions* and *exceptional violations*. Infractions are typically minor violations that are usually tolerated by the organization, whereas exceptional violations are isolated and extreme departures from acceptable practice, neither condoned by the organization nor typical of the operator.

HFACS provides a tool for post-mishap analysis that may provide useful information to those tasked with developing mishap prevention strategies (Shappell & Wiegmann, 1997c). It may also be used to help investigators gain an appreciation for the genesis of human error, and the relationship between the conditions of the operators, and those who supervise them, and the unsafe acts that directly resulted in the mishap. HFACS' cause-oriented approach is also thought to make it useful in a variety of occupational settings, not just aviation. Finally, HFACS can be used as a training tool to

educate operators and their organizations and thereby increase their awareness of human error types and accident causes.

C. ACCIDENT PREVENTION

1. Purpose

The prevention of accidents is clearly a desirable goal in any organization.

McElroy (1974) stated that a successful accident prevention program involves at least four fundamental activities:

1. A study of all working areas to detect and eliminate or control physical or environmental hazards which contribute to accidents;
2. A study of all operating methods and practices;
3. Education, instruction, training and discipline to minimize human factors which contribute to accidents;
4. For cause analysis, a thorough investigation of at least every accident which results in a disabling injury or lost workdays to determine contributing circumstances. (p.151)

This fourth element, accident investigation and analysis, "is a defense against hazards that are overlooked in the first three activities, those that are not obvious, or hazards that are the result of combinations of circumstances that are difficult to foresee" (p. 150).

2. Accident Causation

An implicit assumption of accident analysis has been that if the cause of the accident is known, then similar accidents can be prevented in the future (Mayer & Ellingstad, 1992; Hill, Byers, Rothblum & Booth, 1994). This is often true when the cause of an accident is material in nature; however, accidents caused by human error often leave little direct evidence for later analysis. Therefore, accident databases often contain more information representing hardware failures, and other directly observable phenomena, than human error (Mayer & Ellingstad, 1992).

Heinrich et al. (1980) developed one of the earliest theories of accident causation. His domino theory stated that injuries result from a series of factors in the sequence of events that lead up to an accident: heredity and social environment, faults of a person, unsafe acts and/or mechanical or physical hazards, the accident itself, and finally, the resulting injury. Two central points of this theory are: (1) injuries are caused by the action of preceding factors; and (2) removal of the central factor (unsafe act or hazardous condition) negates the action of the preceding factors and thereby prevents the accident.

A human factors theory of accident causation later described by Heinrich (1980) attributed accidents to a chain of events ultimately caused by human error. Three broad factors that lead to human error were identified as *overload*, *inappropriate activities*, and *inappropriate responses*. Overload refers to an imbalance between a person's task capacity at any given time and the task load that person is carrying in a given state. Factors that affect capacity include a person's natural ability, training, fatigue, stress, and physical condition. Inappropriate activities consist of performing tasks without requisite training or misjudging the degree of risk involved with a given task. Inappropriate responses consist of detecting but not correcting a hazard, removing safeguards from machines and equipment, and ignoring safety.

The accident/incident theory of accident causation also described by Heinrich (1980) added new elements to the human factors theory like ergonomic traps, the decision to err, and systems failures. In this theory, *overload*, *ergonomic traps*, and/or a *decision to err* can lead to human error. Ergonomic traps consist of incompatible workstations and incompatible expectations. The decision to err may be unconscious, conscious and based on logic, or it may be based on a misjudgment of risk. The systems failure

component is a result of these causes of human error and accounts for the potential for a causal relationship between management decisions and behavior, and safety. It also establishes management's role in accident prevention as well as the broader concepts of health and safety in the workplace.

The epidemiological theory of accident causation developed by Suchman (as cited in Heinrich et al., 1980) holds that the models used for studying and determining the causal relationships between environmental factors and disease (epidemiology) can also be used to study causal relationships between environmental factors and accidents.

According to this approach, injuries and damage are the measurable indices of an accident, but the accident itself is the unexpected, unavoidable, and unintentional act resulting from the interaction of the victims of the injury or damage deliverer and environmental factors within situations which involve risk taking and perceptions of danger. ... In applying this approach one seeks an explanation for the occurrence of accidents within the host (accident victim), the agent (injury or damage deliverer), and environmental factors.... (p.50)

The key components of these environmental factors are *predispositional characteristics* and *situational characteristics*. Predispositional characteristics consist of susceptibility of people, perceptions, and environmental factors. Situational characteristics include risk assessment by individuals, peer pressure, priorities of the supervisor, and attitude.

M. Edwards (1981) described an approach for conducting accident investigations with an emphasis on human factors using a model of accident causation called the SHEL system developed by E. Edwards (1972). Three types of system resources, Software (procedures and rules), Hardware (machinery), and Liveware (humans) interact together within their Environment. M. Edwards wrote:

The ergonomics approach to accidents is based on the premise that what people do in a work situation is determined not only by their capabilities

and limitations but also by the machines they work with, the rules and procedures governing their activities and the total environment within which the activity takes place. ... Accidents, then, are symptomatic of a failure in the system and as such provide clues about the location of the source of failure, indicating where mismatches occur and what kind of action is likely to be effective in reducing these mismatches. (p. 114)

Shappell and Wiegmann (1997b) add, however, "until human failure is adequately described, its complex interactions with other components of the SHEL model cannot be fully understood" (p. 271).

Bird (1974) proposed a sequential theory of accident causation where events leading to an accident can be likened to dominos falling. The first domino represents management control of accident prevention. Losses at this level permit personal and job-related causes (domino two) to appear. These causes are often at the root of the sub-standard conditions and practices (domino three) that directly result in an accident (domino four), and lastly, personal injury and material damage. Removal of any of the first three dominoes may then be expected to interrupt the chain and thereby prevent the accident.

There is often a difference between any theory of accident causation and reality. Some accidents may be described by one theory better than by another. Goetsch (1996) described a combination theory of accident causation where the actual cause of an accident may combine parts of different theories. He maintained that safety professionals should use these theories as appropriate for both accident prevention and investigation.

3. Investigations

An accident investigation should produce information that leads to countermeasures that prevent or reduce the number of accidents (McElroy, 1974). Mayer

and Ellingstad (1992) contend that, in addition to gathering factual information about an accident, a human factors analysis should be a major part of an investigation. Human factors analysis refers to a "complete accounting of human-equipment interaction in the accident situation, and not the 'mental state' or disposition of the people involved in the accident" (p. 965). Task demands placed on the operator and operational requirements of the task must be accounted for. "The need for standardization and the realization that not all accident investigations will be conducted by professionals in human factors, suggests that checklists or other 'cookbook' methods may be needed" (p. 966).

There are few methodological tools for the analysis of human factors accidents (Mayer & Ellingstad, 1992; Edwards, 1981; Pimble & O'Toole, 1982). Many methods presented in the literature involve reorganization and analysis of data that has already been collected. Adams, Barlow and Hiddlestone (1981) redesigned an injury report for use in an Australian steel-processing plant that included several checklists to elicit clearly defined, categorical ergonomics data. They then tracked injury rates over a five-year period and observed a dramatic drop in injury frequencies, which they attributed partly to the use of the highly informative and detailed report form. They concluded that the categorical approach to reporting utilized in their study was of real value, and suggestions were made for its more widespread application.

Andersson and Lagerlöf (1983) described changes to the Swedish information system on occupational injuries that included implementing a new injury notification form that provided a sounder basis for accident prevention measures. They viewed their system as an improvement over the previous method of data collection that they described as very case-related and useful primarily as an aid for setting fees for work

injury insurance. Hill et al. (1994) described a computerized investigation reporting system in use by the U.S. Coast Guard which requires investigators to complete standard forms containing specific classification schemes to summarize accident information. They claimed that the system has provided structure to data collection and consistency across investigations.

4. Reporting

To be effective, accident reports must be based on complete and unbiased information regarding the accident. The primary aim of the accident report is to record this information and not to fix blame. Since the accuracy and completeness of any accident database is dependent on the quality of each individual accident report, it is critical that investigators use a standardized reporting format (McElroy, 1974).

Accident investigations typically produce a large quantity and variety of data. Mayer and Ellingstad (1992) discussed how accident databases frequently describe attributes of environment and equipment, but that detailed analysis of accident causes, including human factors information, are frequently not represented because they are too difficult to obtain and code. If one considers a single accident to be symptomatic of a larger organizational safety problem, then analyses into the causes of accidents would logically involve consideration of post-accident data. "Databases that do not attempt to explain more than factual data are generally of little use to human factors researchers" (Mayer & Ellingstad, 1992, p. 966).

Shappell and Wiegmann (1997b) noted that most accident databases are not designed around a theoretical framework of human error. "Indeed, most accident reporting systems are designed and employed by engineers and front-line operators with

limited backgrounds in human factors" (p. 270). This supported their observation that the rates of aviation accidents attributable to material and design factors had decreased significantly over the last 20 years, whereas the rates of accidents attributable to human error have not dropped a comparable amount. "Resulting post-accident databases are therefore not typically conducive to a traditional human error analysis, making the identification and development of viable human intervention strategies onerous" (p. 270).

5. Accident Analysis

There have been a number of efforts described in the literature where some progress was made at extracting causes of accidents from existing databases. Anderson (1983) studied shipboard accident reports by sorting the data by location of accident on specific ships, and then conducted an ergonomic survey and appraisal of the locations to make recommendations for future accident prevention. Studies have been performed on slips and falls in a variety of industrial settings (Andersson & Lagerlöf, 1983; Leamon & Murphy, 1995) and material handling accidents (Pimble & O'Toole, 1982). These studies have provided procedures for extracting accident causes from traditional databases.

Research has been conducted in which post-accident data was reclassified according to various theoretical frameworks of human error. Salminen and Tallberg (1996) examined the effect of human error on industrial accidents in Finland by classifying numerous accidents according to Rasmussen's (1987b) skill-rule-knowledge (SRK) model discussed previously. They found that 84-97 percent of the accidents were due to human error with over half the human errors classified as skill-based and in general the SRK model worked well. O'Hare, Wiggins, Batt, and Morrison (1994) examined human failure in the airline cockpit by recoding data from airline accidents in

New Zealand over a ten year period using Nagel's (1988) model as well as several other cognitive failure models described therein. They found that aircraft accident reports could be a useful source of information about cognitive failures when examined with an appropriate, theoretically-based analysis of information processing errors.

D. SUMMARY

Numerous theories of human error have been postulated. Reason (1990) provided a working definition of error to be all occasions when intended actions fail to achieve the intended outcome for reasons other than chance. Causes of human error evolved from being a result of negative character traits to the inevitable result of human-system performance mismatch. A discrete-action classification model was developed by Swain and Guttman (1983) that included errors of commission, errors of omission, sequence errors, and timing errors. Norman and Lewis (1986) proposed dividing errors into the categories slips and mistakes, and Rasmussen (1987b) described error types as skill-based, rule-based, and knowledge-based.

Nagel (1988) classified error by the stages of information processing in which they occurred: information, decision, and action. Wickens and Flach (1988) used a similar information processing model to describe errors as slips or mistakes, depending on the stage of processing in which they occur. Reason's (1990) model of unsafe acts differentiated between whether the act was intended or not. Unintentional errors were called slips and lapses. Intentional acts that resulted in error were called rule-based or knowledge-based mistakes or routine or exceptional violations. Reason (1995) later presented a theory of accident causation in which he described how active and latent failures contribute to system breakdown. Shappell and Wiegmann (1997b) constructed a

human error taxonomy using several established theories to classify certain aviation mishap causal factors.

Accident prevention was established as a major organizational goal. Heinrich et al. (1980) and Bird (1974) proposed similar domino theories that described an accident as being the last item in a chain of events. Bird maintained that elimination of one or more "links" of the chain could prevent the accident from occurring. Several other theories of accident causation were described and it was noted that some accidents may best be described by a combination of them. Accident investigations were described as vital tools for collecting information about accident causes, though investigations frequently do not uncover the reasons why the identified errors occurred. In general, accident databases do not support human factors analysis. Several attempts have met with some success at extracting human factors information from existing accident databases.

III. METHODOLOGY

A. RESEARCH APPROACH

This research involved analysis of an existing database of mishap reports maintained by the U.S. Navy. These mishap reports cite causal factors contributing to the mishap occurrence as identified by the investigating board. These causal factors were evaluated independently by two judges and the human error factors were classified according to an existing taxonomy of human error types. Both judges were professional naval officers with roughly sixteen years experience each and extensive knowledge of HFACS. One was a submarine officer and the other was an experimental psychologist. The reliability of the taxonomy was evaluated by comparing the level of agreement between the two judges. Differences were resolved and the final classification of all human error causal factors served as the data set for subsequent statistical analysis. The analysis involved calculating the percentage of mishaps in the various categories that had instances of each of the human error types contained in the HFACS taxonomy. Tests for significance between types of causal factors in various groupings of the mishaps were performed.

B. DATA COLLECTION

1. Afloat Mishaps

A comprehensive review of Navy Class A mishaps involving ships, submarines, and diving units between January, 1992, and December 1996, was conducted using the mishap database maintained by the Naval Safety Center, Norfolk, Virginia. The Navy classifies a mishap according to the severity of the accident. Class A mishaps involve

one or more of the following: (1) a total cost of \$1,000,000 or more, (2) a fatal injury, or (3) a permanent total disability. Class A mishaps occurring prior to 1992 were not reviewed because the information maintained in the electronic database did not contain a complete record of mishap causal factors needed for this analysis.

2. Human Factors Accident Classification System

The HFACS taxonomy used in this analysis contained categories for classifying causal factors and was organized into three levels as shown in Table 1. At the broadest level, mishap causal factors are classified as unsafe acts of the operator, unsafe conditions of the operator, and unsafe supervision. Levels II and III contain the detailed breakdown of the preceding higher level (where applicable).

LEVEL I	LEVEL II	LEVEL III	CODE
Unsafe Acts	Errors	Perceptual	1
		Skill-Based	2
		Decision	3
	Violations	Infraction	4
		Exceptional Violation	5
Unsafe Conditions	Medical Conditions	Adverse Physiological State	6
		Adverse Mental State	7
		Physical/Mental Limitation	8
	Crew Resource Management	Crew Resource Management	9
	Personnel Readiness	Personnel Readiness	10
Unsafe Supervision	Unforeseen Unsafe Supervision	Unrecognized Hazardous Operation	11
		Inadequate Documentation	12
		Inadequate Design	13
	Known Unsafe Supervision	Inadequate Supervision	14
		Planned Inappropriate Action	15
		Failure to Correct Problem	16
		Supervisory Violation	17

Table 1. Human Factors Accident Classification System Taxonomy.

3. HFACS Procedure

Copies of each of the final mishap investigation board reports, including comments from all endorsements by the chain of command, were provided to two judges. Each human error causal factor cited in the mishap reports was independently classified by the two judges according to which one of the 17 taxonomy codes identified in Table 1 they considered best reflected the causal factor description. All classification differences between the judges were unanimously resolved yielding a single classification of each of the causal factors.

4. Ten-Year Class A Mishap History

Though only 46 mishap reports were available for detailed HFACS analysis, the dates of afloat Class A mishaps over the period 1987 through 1996 were extracted from the electronic database at the Naval Safety Center. Additionally, the number of commissioned ships over this period was collected to allow analysis of mishap rates.

C. DATA ANALYSIS

1. Data Tabulation

The occurrence of one or more instance of each error type in each mishap was recorded in a spreadsheet. Multiple occurrences of the same error type in a single mishap received no more weight than a single occurrence due to the wide variability in length and detail of the mishap reports.

2. Statistical Analysis

a. Frequency Analysis of Mishaps

The percentages of mishaps by mishap type and then by ship type were determined. Next, the numbers of mishaps by ship type and mishap type were

determined. Fatal mishaps were then categorized and the percentages of these categories were determined. In order to describe the distribution of causal factor citations in the mishaps, the minimum, maximum, and mean number per mishap, as well as the total number cited for each mishap type, were determined.

b. Inter-Rater Agreement

The reliability of the HFACS taxonomy was evaluated by calculating inter-rater agreement between the two judges using Cohen's kappa. Kappa is an index of agreement that has been corrected for chance (Fleiss, 1981). Kappa values were calculated for the three levels of causal factor classification. Fleiss (1981) characterized different ranges of values for kappa with respect to the degree of agreement they suggest. For most purposes, kappa values between 0.75 and 1.00 indicate excellent agreement, values between 0.40 and 0.75 indicate good agreement, and values below 0.40 indicate poor agreement beyond chance. These characterizations were used to evaluate the inter-rater agreement at the three different levels of taxonomy classification identified in Table 1.

c. Frequency Analysis of HFACS

The percentage of mishaps, both in aggregate and by mishap type and ship type, which contained at least one causal factor classified in the nine categories in Level II of the taxonomy were determined. Differences between mishap types and by ship type were evaluated.

d. Mishap Group Comparisons

Each mishap report contained categorical information regarding the mishap ship which included local time of day of the mishap (day or night), the physical

location of the mishap unit (at sea or in port), and the fleet to which the mishap unit was assigned (Atlantic or Pacific). Each mishap was grouped into one of two possible choices for each of these categories and a test was performed to determine if there was a significant difference between the HFACS causal factor "signature" of each dichotomous grouping. A permutation test (Sprent, 1989) was performed for this evaluation. An extensive discussion of the test is provided in Appendix A.

e. Ten-Year Mishap Frequency Analysis

The frequency and rate of all afloat class A mishaps by calendar quarter during the period 1987 through 1996 were examined to provide a broader perspective of the 46 mishaps analyzed by HFACS. This information may be useful for future evaluation of measures initiated as a result of this research.

IV. RESULTS

A. MISHAP DATABASE

A total of 59 Class A mishaps occurred during the period from January, 1992, through December, 1996. Of these 59 mishaps, 46 had mishap investigation board reports available for review. Though limited data on all Class A mishaps is maintained indefinitely in an electronic database at the Naval Safety Center, a mishap investigation report was not available for the remaining 13 mishaps for one of the following reasons: (1) a mishap investigation was not conducted because the mishap was determined to be due to a material failure only, and not the result of human error; (2) the report had been disposed of because of exceeding the Naval Safety Center's retention requirement; or (3) the report could not be located. A summary of the database is provided in the Appendix

B.

A breakout of maritime class A mishaps by ship types *Carriers*, *Combatants*, *Auxiliaries*, *Amphibs*, and *Other* is provided in Figure 1. Eleven of the 46 mishaps (24%) occurred on aircraft carriers. Fourteen mishaps (30%) occurred on combatants (i.e., cruisers, destroyers, frigates, and submarines), and 11 (24%) occurred on auxiliary ships (i.e., oilers, ammunition ships, and repair ships). Four mishaps (9%) occurred on amphibious-type ships (i.e., helo transport and troop ships). The "Other" category represents six mishaps (13%) that occurred on diving units, tugs, and assault craft.

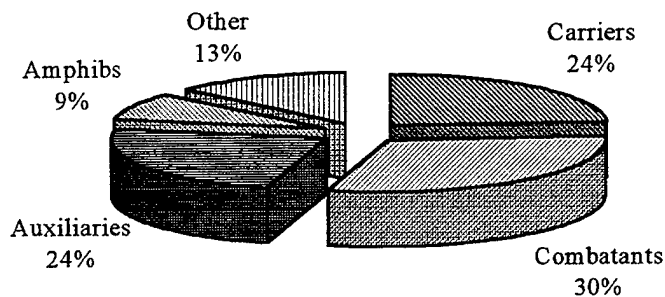


Figure 1. Distribution of Mishaps by Ship Type.

A breakout of the maritime class A mishaps by type is shown in Figure 2.

Twenty-seven mishaps (59%) reviewed were categorized as fatalities (note: 26 involved one or more fatalities and one resulted in a permanent total disability) and 19 (41%) involved equipment damage. Of the 19 equipment damage mishaps, 12 involved the collision or grounding of a vessel.

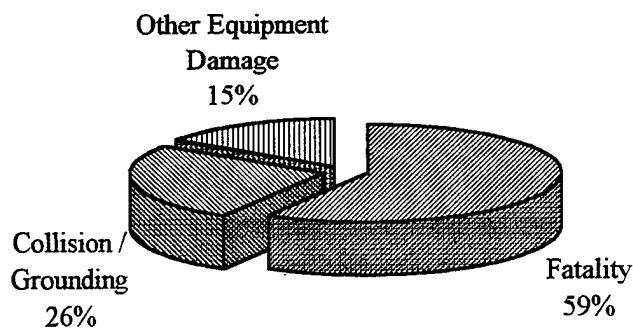


Figure 2. Distribution of Mishaps by Mishap Type.

A breakout of the 46 mishaps sorted by ship type and mishap type is shown in Figure 3. Auxiliary ships accounted for the largest number of fatal mishaps with nine, followed next by carriers with seven; and four fatal diving mishaps and one fatal tug mishap fall in the "Other" category. Combatant ships experienced by far the largest

number of collisions and groundings with eight. No other ship type had more than two collision or grounding mishaps. "Other equipment damage" mishaps were nearly equally distributed between the ship types. This category involved three propulsion equipment casualties, one fire, one flooding, a lost towed sonar device, and a hydraulic system contamination.

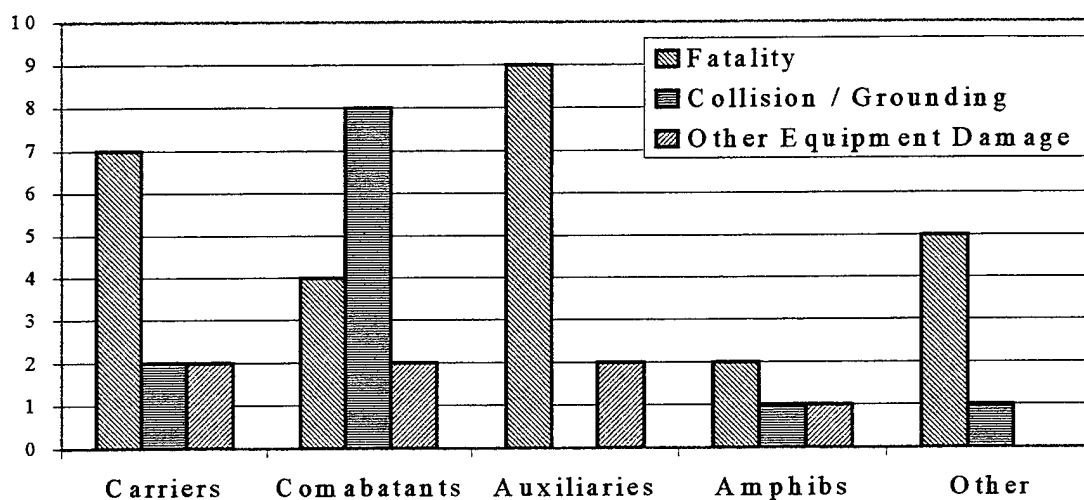


Figure 3. Distribution of Mishap by Mishap Type and Ship Type.

The 27 fatal mishaps were distributed into four broad categories shown in Figure 4. Ten "General" fatal mishaps (36%) occurred involving fires, forklift operation, line-handling, material handling, electric shocks, or falls. Five diving mishaps (19%) that involved the diver either drowning or experiencing a fatal embolism were analyzed. Five fatal mishaps (19%) occurred during scheduled maintenance performance on cargo elevators, CO₂ sprinkler systems, and electronic equipment. Seven man-overboard mishaps (26%) occurred where the victim was either battered against the ship's hull or drowned before being rescued.

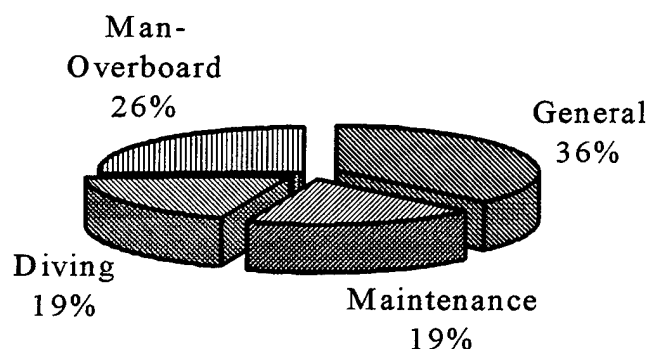


Figure 4. Distribution of Fatal Mishaps by Type.

A total of 496 causal factors were cited in the 46 mishaps, and included mishap causes relating to human error, material, and environmental factors. The number of causal factors cited in each of the mishap reports varied greatly. Table 2 shows the frequency of causal factor citations in each of the three mishap categories. The twenty-seven fatal mishaps had the lowest mean number of causal factors cited per mishap with 7.0, while equipment damage mishaps not involving grounding or collision had the highest mean of 18.7 causal factors cited per mishap. Collision and grounding mishaps were in between these values with a mean of 14.6 causal factors cited per mishap.

Mishap Type	Number of Causal Factors Cited	Number of Causal Factors Cited per Mishap		
		Minimum	Maximum	Mean
Fatality (27)	190	1	24	7.0
Collision/Grounding (12)	175	3	38	14.6
Other Equipment Damage (7)	131	4	38	18.7

Table 2. Distribution of Number of Causal Factors Cited by Mishap Type.

The mishap reports contained information provided in Table 3 that was specific to the mishap unit including to which Navy fleet the unit belonged, the physical location of

the mishap unit at the time of the mishap, and the local time of day at which the mishap occurred. Twenty-seven of the 46 mishaps analyzed (58.7%) were under the responsibility of the Commander In Chief, U.S. Atlantic Fleet (CINCLANTFLT), and the remaining 19 (41.3%) belonged to the Commander in Chief, U.S. Pacific Fleet (CINCPACFLT). Nineteen of the 46 mishaps (41.3%) occurred while the ship or unit was located in port, while the remaining 27 (58.7%) occurred at sea. Thirty-two of the 46 mishaps (69.6%) occurred during the hours from 0600 to 1800 local time and the remaining 14 (30.4%) occurred after normal working hours between 1800 through the night until 0600.

Mishap Unit Facts	% Total (n = 46)	% Fatality (n = 27)	% Collision & Grounding (n = 12)	% Other Equipment Damage (n = 7)
<u>Fleet Association</u>				
Atlantic	58.7 (27)	59.3 (16)	58.3 (7)	57.1 (4)
Pacific	41.3 (19)	40.7 (11)	41.7 (5)	42.9 (3)
<u>Physical Location</u>				
In Port	41.3 (19)	59.3 (16)	0.0 (0)	42.9 (3)
At Sea	58.7 (27)	40.7 (11)	100.0 (12)	57.1 (4)
<u>Mishap Time of Day</u>				
Day (0600-1800)	69.6 (32)	81.5 (22)	58.3 (7)	42.9 (3)
Night (1800-0600)	30.4 (14)	18.5 (5)	41.7 (5)	57.1 (4)

Table 3. Comparison of Mishaps by Mishap Unit Facts. The number represents the percentage of mishaps in the mishap category that corresponds to the associated grouping followed by the raw number of mishaps in parentheses.

B. HUMAN FACTORS ACCIDENT CLASSIFICATION SYSTEM

Using the HFACS taxonomy, 459 (92.5%) of the 496 of the causal factors identified in the mishap reports were classified by both judges as human error. The

remaining 37 causal factors were classified as being either a material or environmental issue. Inter-rater reliabilities for classification of the 459 factors into the various levels of the taxonomy (from Table 1) are provided in Table 4. The best agreement between the judges was at Level I of the taxonomy ($\kappa = 0.64$), where the causal factors are categorized as being an unsafe act, unsafe condition, or unsafe supervision. This "kappa" value represents good agreement between the two judges, as did the values for the other two levels. Consensus was reached between the two judges for all differences in classification for the 459 causal factors, which became the data set for subsequent analysis.

Taxonomy Level	Number of Factors in Level	Inter-Rater Reliability (kappa)
I	3	0.64
II	7	0.54
III	17	0.43

Table 4. Comparison of Inter-Rater Reliability "Kappa" Value by Taxonomy Level.

C. AFLOAT MISHAP HFACS CAUSAL FACTOR CLASSIFICATION

The distribution of the 459 causal factors over all mishaps at Level II (seven factors) of HFACS is shown in Figure 5. Known supervisory error comprised the largest segment with 196 (42.7%) causal factors, followed by the operator error categories with 104 (22.7%) and crew resource management with 57 (12.4%) causal factors.

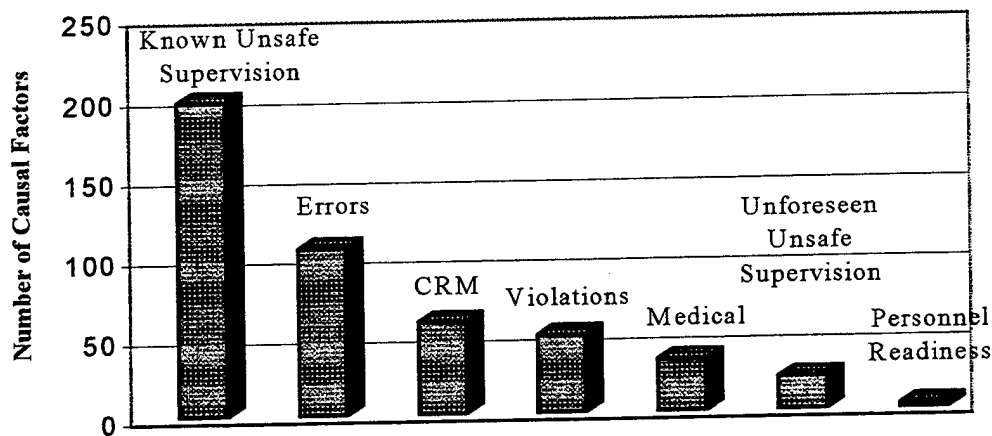


Figure 5. Distribution of All Mishap Causal Factors at HFACS Level II.

The distribution of the 459 human error causal factors by mishap type and ship type for the 46 mishaps are provided in Tables 5 and 6 respectively. Table 5 shows the percentage of mishaps for which reports cited each HFACS causal factor, broken down by mishap type. In general, known unsafe supervision was strongly associated with all mishaps (all types greater than 66%). Crew resource management errors and inadequate supervision were most frequently associated with collisions and groundings (both 83.3%). Skill-based errors and inadequate supervision were most frequently associated with mishaps categorized as "Other Equipment Damage" (both 85.7%). Inadequate supervision and decision errors were most frequently associated with fatal mishaps (66.7% and 51.9%, respectively).

Taxonomy Causal Factor	% Total (n = 46)	% Fatality (n = 27)	% Collision & Grounding (n = 12)	% Other Equipment Damage (n = 7)
<u>Unsafe Acts</u>				
Perceptual Error	6.5 (3)	7.4 (2)	8.3 (1)	0.0 (0)
Skill-Based Error	50.0 (23)	40.7 (11)	50.0 (6)	85.7 (6)
Decision Error	56.5 (26)	51.9 (14)	66.7 (8)	57.1 (4)
Infraction	32.6 (15)	29.6 (8)	33.3 (4)	42.9 (3)
Exceptional Violation	28.3 (13)	14.8 (4)	41.7 (5)	57.1 (4)
<u>Unsafe Conditions</u>				
Adverse Physiological State	6.5 (3)	11.1 (3)	0.0 (0)	0.0 (0)
Adverse Mental State	30.4 (14)	29.6 (8)	41.7 (5)	14.3 (1)
Mental/Physical Limitation	2.2 (1)	3.7 (1)	0.0 (0)	0.0 (0)
Crew Resource Management	34.8 (16)	14.8 (4)	83.3 (10)	28.6 (2)
Personnel Readiness	4.3 (2)	7.4 (2)	0.0 (0)	0.0 (0)
<u>Unsafe Supervision</u>				
Unrecognized Hazardous Ops	4.3 (2)	7.4 (2)	0.0 (0)	0.0 (0)
Inadequate Documentation	10.9 (5)	3.7 (1)	16.7 (2)	28.6 (2)
Inadequate Design	15.2 (7)	22.2 (6)	0.0 (0)	14.3 (1)
Inadequate Supervision	73.9 (34)	66.7 (18)	83.3 (10)	85.7 (6)
Planned Inappropriate Actions	32.6 (15)	33.3 (9)	33.3 (4)	28.6 (2)
Fail to Correct Problem	17.4 (8)	11.1 (3)	8.3 (1)	57.1 (4)
Supervisory Violation	28.3 (13)	25.9 (7)	16.7 (2)	57.1 (4)

Table 5. Comparison of Mishaps by HFACS Causal Factor Category. The number represents the percentage of mishaps in the mishap category that contained at least one instance of the corresponding taxonomy causal factor followed by the raw number of mishaps in parentheses.

Table 6 shows the percentage of mishap reports, by ship type, that cited at least one instance of a causal factor in the various HFACS taxonomy categories. In general, decision errors and inadequate supervision were most closely associated with carriers (72.7% and 90.9%, respectively). Decision errors and inadequate supervision were also strongly associated with combatants (64.37% and 85.7%, respectively). Skill-based errors were most closely associated with the "Other" category (66.7%), consisting of fatal mishaps on four diving units and a tug, and an assault craft (LCAC) grounding. All ship types had known unsafe supervision cited in well over half of their mishaps.

Taxonomy Causal Factor	% Carriers (n = 11)	% Combatants (n = 14)	% Auxiliaries (n = 11)	% Amphibs (n=4)	% Others (n=6)
<u>Unsafe Acts</u>					
Perceptual Error	9.1 (1)	7.1 (1)	0.0 (0)	0.0 (0)	16.7 (1)
Skill-Based Error	36.4 (4)	57.1 (8)	45.5 (5)	50.0 (2)	66.7 (4)
Decision Error	72.7 (8)	64.3 (9)	63.6 (7)	25.0 (1)	16.7 (1)
Infraction	36.4 (4)	35.7 (5)	27.3 (3)	50.0 (2)	16.7 (1)
Exceptional Violation	18.2 (2)	35.7 (5)	27.3 (3)	50.0 (2)	16.7 (1)
<u>Unsafe Conditions</u>					
Adverse Physiological State	9.1 (1)	0.0 (0)	9.1 (1)	0.0 (0)	16.7 (1)
Adverse Mental State	45.5 (5)	21.4 (3)	27.3 (3)	0.0 (0)	50.0 (3)
Mental/Physical Limitation	0.0 (0)	0.0 (0)	0.0 (0)	25.0 (1)	0.0 (0)
Crew Resource Management	45.5 (5)	57.1 (8)	18.2 (2)	0.0 (0)	16.7 (1)
Personnel Readiness	0.0 (0)	7.1 (1)	0.0 (0)	0.0 (0)	16.7 (1)
<u>Unsafe Supervision</u>					
Unrecognized Hazardous Ops	0.0 (0)	0.0 (0)	9.1 (1)	0.0 (0)	16.7 (1)
Inadequate Documentation	18.2 (2)	21.4 (3)	0.0 (0)	0.0 (0)	0.0 (0)
Inadequate Design	18.2 (2)	7.1 (1)	18.2 (2)	25.0 (1)	16.7 (1)
Inadequate Supervision	90.9 (10)	85.7 (12)	63.6 (7)	75.0 (3)	33.3 (2)
Planned Inappropriate Actions	36.4 (4)	21.4 (3)	27.3 (3)	25.0 (1)	66.7 (4)
Fail to Correct Problem	27.3 (3)	14.3 (2)	9.1 (1)	0.0 (0)	33.3 (2)
Supervisory Violation	27.3 (3)	42.9 (6)	27.3 (3)	25.0 (1)	0.0 (0)

Table 6. Comparison of Mishap Ship Types by HFACS Causal Factor Category. The number represents the percentage of mishaps in the mishap ship category that contained at least one instance of the corresponding taxonomy causal factor followed by the raw number of mishaps in parentheses.

Table 7 provides the distribution of causal factors among the different types of fatal mishaps. The "General" type of fatal mishap was most closely associated with inadequate supervision (90%), decision errors (60%), and infractions (60%). Man overboard mishaps were most closely associated with inadequate supervision (57.1%), decision errors (42.9%), and adverse mental state (42.9%). Maintenance-related fatal mishaps were most closely associated with inadequate supervision (100%) and decision errors (60%). Diving mishaps, which contained very few causal factor citations (19 total), had no particular causal factor type with which they were most closely associated.

Taxonomy Causal Factor	% All Fatal Mishaps (n = 27)	% General (n = 10)	% Man Overboard (n = 7)	% Maintenance (n=5)	% Diving (n = 5)
<u>Unsafe Acts</u>					
Perceptual Error	7.4 (2)	0.0 (0)	14.3 (1)	0.0 (0)	20.0 (1)
Skill-Based Error	40.7 (11)	50.0 (5)	28.6 (2)	40.0 (2)	40.0 (2)
Decision Error	51.9 (14)	60.0 (6)	42.9 (3)	60.0 (3)	40.0 (2)
Infraction	29.6 (8)	60.0 (6)	14.3 (1)	20.0 (1)	0.0 (0)
Exceptional Violation	14.8 (4)	10.0 (1)	0.0 (0)	40.0 (2)	20.0 (1)
<u>Unsafe Conditions</u>					
Adverse Physiological State	11.1 (3)	10.0 (1)	14.3 (1)	0.0 (0)	20.0 (1)
Adverse Mental State	29.6 (8)	20.0 (2)	42.9 (3)	20.0 (1)	40.0 (2)
Mental/Physical Limitation	3.7 (1)	0.0 (0)	0.0 (0)	20.0 (1)	0.0 (0)
Crew Resource Management	14.8 (4)	30.0 (3)	14.3 (1)	0.0 (0)	0.0 (0)
Personnel Readiness	7.4 (2)	0.0 (0)	0.0 (0)	20.0 (1)	20.0 (1)
<u>Unsafe Supervision</u>					
Unrecognized Hazardous Ops	7.4 (2)	0.0 (0)	14.3 (1)	0.0 (0)	20.0 (1)
Inadequate Documentation	3.7 (1)	10.0 (1)	0.0 (0)	0.0 (0)	0.0 (0)
Inadequate Design	22.2 (6)	30.0 (3)	0.0 (0)	40.0 (2)	20.0 (1)
Inadequate Supervision	66.7 (18)	90.0 (9)	57.1 (4)	100.0 (5)	0.0 (0)
Planned Inappropriate Actions	33.3 (9)	40.0 (4)	14.3 (1)	40.0 (2)	40.0 (2)
Fail to Correct Problem	11.1 (3)	0.0 (0)	14.3 (1)	0.0 (0)	40.0 (2)
Supervisory Violation	25.9 (7)	40.0 (4)	14.3 (1)	40.0 (2)	0.0 (0)

Table 7. Comparison of Fatal Mishap Type by HFACS Causal Factor Category. The number represents the percentage of fatal mishaps in the mishap type category that contained at least one instance of the corresponding taxonomy causal factor followed by the raw number of mishaps in parentheses.

D. MISHAP GROUP COMPARISONS

A permutation test was performed to determine if there was a significant difference in the distribution of causal factor types between the two levels in each of the three groups of mishap unit facts shown previously in Table 3. The test revealed that there was not a significant difference between the distribution of causal factor types in all mishaps in Atlantic or Pacific Fleet units, or those occurring in port or at sea, or during the day or night. The permutation test did, however, reveal there was a significant difference ($p < .01$) between the distribution of causal factor types of the 27 fatal mishaps

and the 19 equipment damage mishaps (collisions, groundings, and other equipment damage mishaps). Complete details of the permutation test are provided in Appendix A.

E. TEN-YEAR MISHAP FREQUENCY ANALYSIS

The frequency of afloat class A mishaps by calendar quarter from 1987 through 1996 is shown in Figure 6. Also shown is the number of commissioned Navy ships by quarter during the same period. Figure 7 shows the rate of mishaps per ship per calendar quarter during the same ten-year period. These results show that as the number of ships steadied at about 375 from 1994 through 1996, there was an average of 3.4 class A mishaps per year. The data used to generate Figures 6 and 7 is provided in Appendix C.

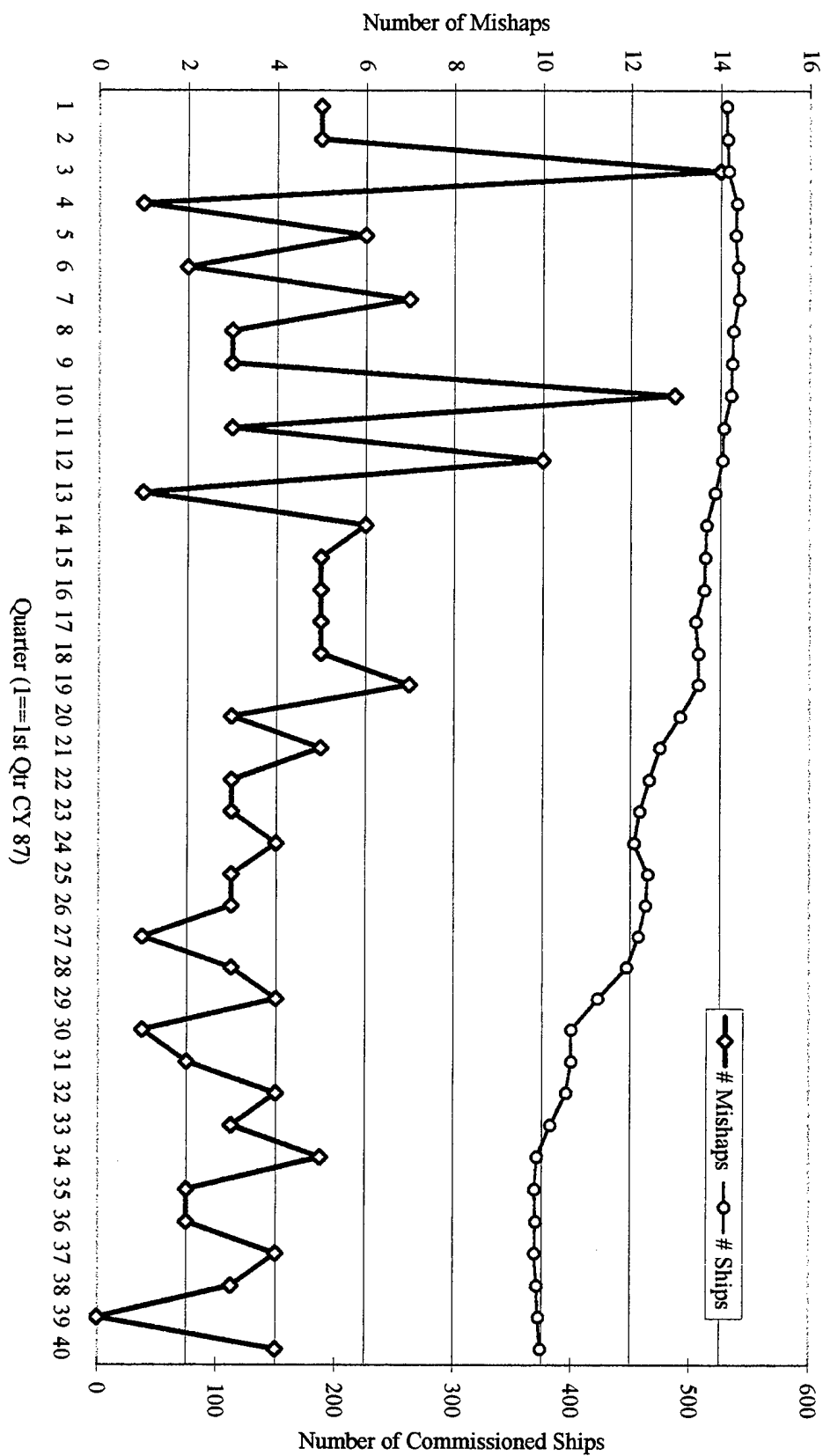


Figure 6. Afloat Class A Mishap Frequency per Calendar Quarter (1987 - 1996)

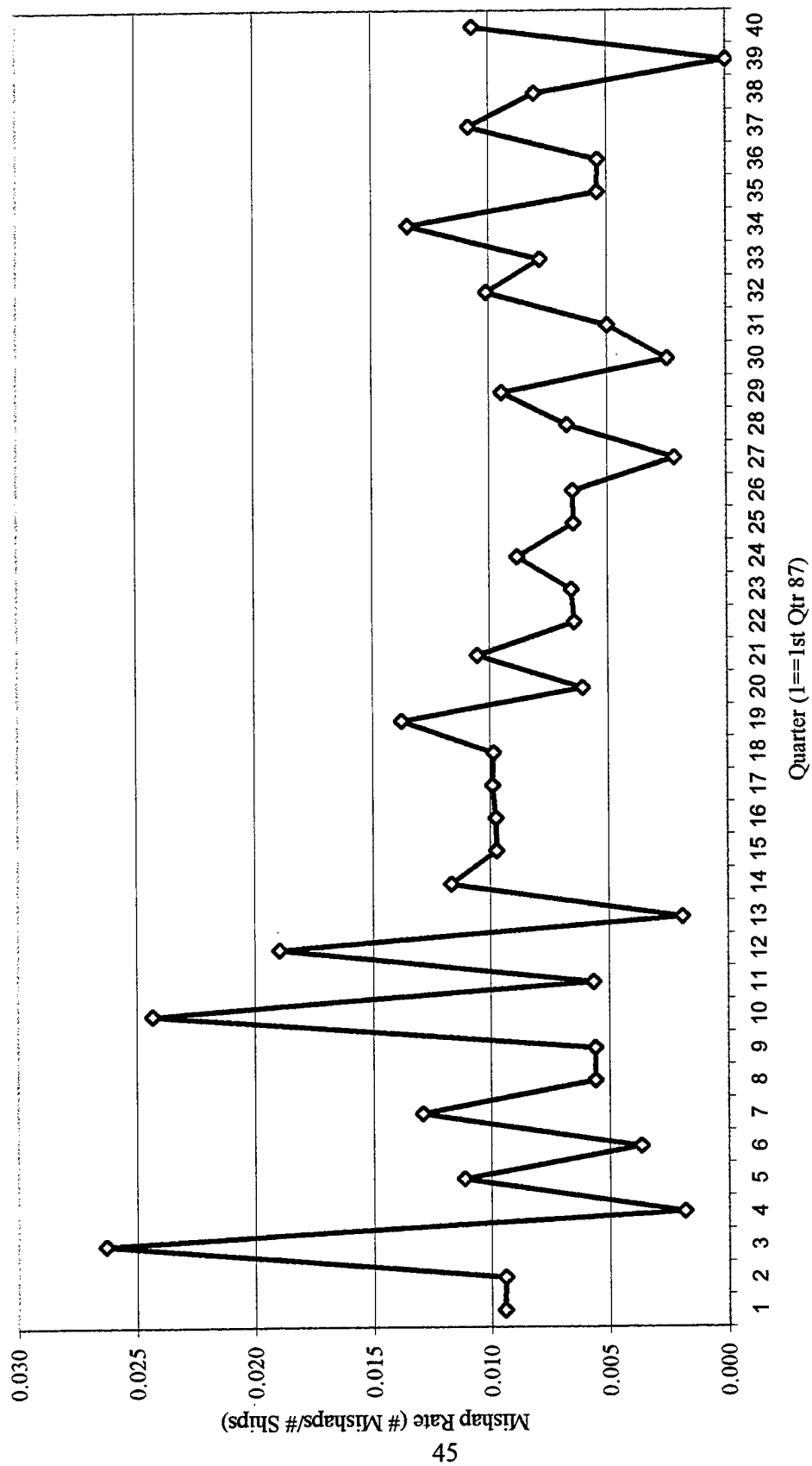


Figure 7. Afloat Class A Mishap Rate per Calendar Quarter (1987 - 1996)

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The effects of maritime mishaps, which include loss of life as well as environmental and economic considerations, are significant. It is estimated that over 80 percent of maritime accidents are at least partially attributable to human error. Human error has been extensively studied in a number of fields, particularly aviation. The present research involves evaluation of a taxonomy, called the Human Factors Accident Classification System (HFACS), for applicability, reliability, and usefulness in the *post hoc* analysis of mishap investigation reports of 46 significant mishaps (i.e., involving a fatality, permanent disability, or equipment damage exceeding \$1 million) that occurred on U.S. Navy ships and submarines between 1992 and 1996. HFACS was developed by personnel at the Naval Safety Center in Norfolk, Virginia, as an application of existing human error theories to accident investigation and analysis. This system has already been adopted by the Navy and Marine Corps for use in aviation mishap investigation and analysis.

The research determined that the taxonomy supported classification of over 90 percent of 496 causal factors cited in the reports. The remaining causal factors involved material and environmental issues. The reliability of the taxonomy for use in ship and submarine mishap analysis was evaluated by comparing the level of agreement between two judges with equivalent understanding of HFACS as they independently classified the mishaps per the taxonomy. Agreement between the two judges was determined to be good.

Differences in causal factor classification between the judges were resolved by consensus and the resulting classifications were used for subsequent exploratory data analysis. This analysis consisted of sorting the data by mishap types (fatality, collision/grounding, or other equipment damage) and ship type (carrier, combatant, auxiliary, amphibious, and other). Fatal mishaps were further sorted by type (general, diving, maintenance, or man-overboard). Each mishap had instances of the different error types, and the percentages of mishaps with each of the error types were determined. A significant difference was found between the types of errors cited in mishaps involving fatalities and those involving equipment damage only.

B. CONCLUSIONS

This research indicated that HFACS was indeed applicable to the analysis of afloat Navy mishaps. The taxonomy contained categories into which each human error causal factor could be classified. In some cases, causal factors cited in the mishap reports could have been classified equally well into more than one categories. Discussion between the judges revealed that this was more a criticism of the causal factor descriptions than a criticism of the taxonomy. There was a wide range of specificity in the wording of the causal factor descriptions in the mishaps reports analyzed. This is not to be unexpected, given that no two mishap investigation boards had the same membership, and the governing instructions for mishap reporting contain nothing as specific as the HFACS taxonomy to guide the investigation and reporting processes.

The fact that a significant difference was found between the types of causal factors cited in fatal mishaps and equipment damage mishaps indicates that prevention strategies for these two broad categories of mishaps should be pursued independently.

Conversely, the fact that significant differences in causal factor types were not evident with respect to mishap unit fleet origin, physical location, or mishap time of day indicates that prevention strategies for these categories of mishaps should be pursued in aggregate.

C. RECOMMENDATIONS

To achieve greater benefit from the HFACS taxonomy, it is recommended that the Naval Safety Center consider leading an effort to revise the instruction governing afloat mishap investigation and reporting, OPNAVINST 5100.19. The revision should include a discussion of HFACS and provide guidance to mishap investigation boards for implementing HFACS as they analyze mishap circumstances.

Post-accident analysis of mishaps involving equipment damage and those leading to fatalities, and the development of their intervention strategies, should be conducted separately. Additionally, application of HFACS to the analysis of less severe, though high-interest, mishaps should be aggressively pursued. Electric-shock, back injury, and toxic substance exposure mishap analysis should be included in this initial expansion of HFACS application.

Finally, the Naval Safety Center should initiate efforts to modify their electronic database to better support human factor analysis of afloat mishap data. Specifically, entire causal factor descriptions and the corresponding HFACS taxonomy classification should be maintained in the database for each mishap causal factor.

APPENDIX A. PERMUTATION TEST DESCRIPTION

To determine if the types of mishap causal factors identified in one grouping of mishaps are different from another, a permutation test (Sprent, 1989) was devised. This test compared a test statistic derived from the actual dichotomous groupings of mishaps to one derived from a randomized grouping of the same sizes from the mishap population.

The 46 mishaps analyzed in this research consisted of 27 mishaps involving one or more fatalities or permanent total disabilities and 19 involving damage to equipment exceeding \$1 million. To determine if there was a significant difference between the types of causal factors cited in these two groupings, a test statistic was computed. For each group of mishap types, 17 proportions representing the frequency of occurrences of the 17 HFACS causal factor types were computed. The test statistic was the sum of the squared differences of the 17 proportions between the two groups. That is, let a_i represent the proportion of mishaps in group a in which one or more instances of HFACS causal factor i was cited. Let b_i represent the same thing for mishap group b . The test statistic is therefore equal to:

$$\sum_{i=1}^{17} (a_i - b_i)^2$$

Calculation of this same statistic was then performed for repeated random samplings (without replacement) of groups of 27 and 19 from the 46 mishap population. A simple hypothesis test was made:

Null Hypothesis:

The difference in causal factor types between fatal mishaps and equipment damage mishaps is no different from a random distribution of the 46 mishaps into one group of 27 and another of 19.

Alternate Hypothesis:

There is a significant difference in causal factor types for the fatal mishaps and equipment damage mishaps compared to random groupings of the incidents into sets of 27 and 19.

The test statistic for this hypothesis is the mean number of times the actual statistic value is greater than the statistics computed for the random groupings. The decision rule is to reject the null hypothesis if this test statistic is greater than 0.975 or less than 0.025, representing a 0.05 level of significance. The test is two-tailed since it was considered unknown whether the actual grouping's statistic would be greater than or less than the statistic from the permutation test.

This permutation test was applied to the research data using a function written in the programming language of the statistical software package S-Plus® (1997) as follows:

```
function(n = 5000, df)
{
#
# Permutation Test for Comparing Two Distributions
#
# Arguments: n = number of simulations
#            df = data frame, 46x(17+1),
#                with the last column being 1 for
#                fatalities and 0 for others.
#
# The statistic of interest will be  $\sum (f_i - e_i)^2$ , where
#  $f_i$  is the proportion of fatal mishaps with one or more
# occurrence of causal factor  $i$  and  $e_i$  is the same
# proportion for equipment damage mishaps. The hypothesis
```

```

# is that this statistic doesn't depend on the way the 46
# incidents are divided into groups.
#
# Here's the statistic of interest for the real division
# into groups.
#
  f.tot <- apply(df[df[, 18] == 1, -18], 2, sum)
  e.tot <- apply(df[df[, 18] == 0, -18], 2, sum)
  fl.tot <- f.tot/27
  el.tot <- e.tot/19
  baseline <- sum((el.tot - fl.tot)^2)
  stat <- numeric(n)

#
# Now to sample of nineteen numbers from 1 to 46; let that
# 19 be the equipment damage mishaps and the other 27 be
# fatal mishaps; and compute the statistic we would have
# seen if that were the true split. This random sampling
# is performed n times through the for loop.
#
  for(i in 1:n) {
    samp <- sample(1:46)[1:19]
    a.tot <- apply(df[samp, -18], 2, sum)
    b.tot <- apply(df[- samp, -18], 2, sum)
    al.tot <- a.tot/19
    bl.tot <- b.tot/27
    stat[i] <- sum((al.tot - bl.tot)^2)
  }

#
# Now to determine how often would one would see a
# statistic at least as big as the one we did see for the
# actual distribution of fatal mishaps and equipment damage
# mishaps.
#
  return(mean(baseline > stat))
}

```

The "data-frame" consisted of a matrix of 46 rows and 18 columns. Each row corresponded to a different mishap; columns one through 17 represented the 17 causal factor types, and the last column was an indicator variable identifying the group to which the mishap belonged. A cell in column one through 17 would have a "1" in it if the mishap corresponding to that row had one or more citations of that causal factor type cited in its mishap report. The value returned by the function is the proportion of times the "baseline" statistic is greater than the random statistic and represents a true p-value. This function's code was modified by adjusting the split of the 46 mishaps in order to test

for significant differences between the other groupings reported in the body of this thesis. For example, testing for significance in the differences in causal factor types between mishaps occurring during the day and night involved a split of 32 daytime mishaps and 14 that occurred at night.

APPENDIX B. MISHAP DATABASE SUMMARY

MISHAP NUMBER	MISHAP DATE (YYMMDD)	SHIP TYPE	SHIP SUBTYPE	MISHAP TYPE	MISHAP SUBTYPE	# HUMAN ERROR FACTORS CITED
1	920222	COMBATANT	DDG	FATALITY	GENERAL	9
2	920310	AMPHIB	LKA	FATALITY	GENERAL	4
3	920321	COMBATANT	FFG	EQPT DAMAGE	GROUNDING	3
4	920620	COMBATANT	DD	EQPT DAMAGE	COLLISION	5
5	920730	AMPHIB	LST	FATALITY	MAINTENANCE	6
6	920918	CARRIER	CV	FATALITY	GENERAL	5
7	921013	COMBATANT	CG	FATALITY	MOB	1
8	921104	AUXILIARY	AD	FATALITY	GENERAL	16
9	921204	AUXILIARY	AS	FATALITY	DIVING	1
10	930202	OTHER	LCAC	EQPT DAMAGE	GROUNDING	10
11	930325	AUXILIARY	AO	EQPT DAMAGE	OTHER	33
12	930327	OTHER	DIVE	FATALITY	DIVING	1
13	930524	AUXILIARY	T-AO	FATALITY	MOB	3
14	930525	AMPHIB	LPH	EQPT DAMAGE	COLLISION	12
15	930627	OTHER	TUG	FATALITY	MOB	4
16	930915	AUXILIARY	AO	FATALITY	GENERAL	7
17	931007	AUXILIARY	AE	FATALITY	MAINTENANCE	5
18	931217	CARRIER	CVN	FATALITY	MOB	1
19	940202	OTHER	DIVE	FATALITY	DIVING	9
20	940203	AMPHIB	LHA	EQPT DAMAGE	OTHER	4
21	940311	CARRIER	CV	EQPT DAMAGE	OTHER	36
22	940313	COMBATANT	SSN	EQPT DAMAGE	GROUNDING	25
23	940405	OTHER	DIVE	FATALITY	DIVING	6
24	940711	CARRIER	CVN	EQPT DAMAGE	OTHER	20
25	940908	COMBATANT	DD	FATALITY	MAINTENANCE	10
26	941018	AUXILIARY	AOR	FATALITY	MOB	1
27	941023	COMBATANT	FFG	EQPT DAMAGE	OTHER	10
28	941107	COMBATANT	SSN	EQPT DAMAGE	COLLISION	6
29	941122	CARRIER	CVN	FATALITY	MOB	8
30	950120	CARRIER	CVN	FATALITY	MAINTENANCE	3
31	950322	COMBATANT	SSN	EQPT DAMAGE	OTHER	8
32	950520	COMBATANT	CG	FATALITY	GENERAL	24
33	950605	CARRIER	CVN	EQPT DAMAGE	COLLISION	15
34	950613	AUXILIARY	AS	FATALITY	GENERAL	14
35	950629	AUXILIARY	AO	EQPT DAMAGE	OTHER	8
36	950711	OTHER	DIVE	FATALITY	DIVING	2
37	950827	COMBATANT	FFG	EQPT DAMAGE	GROUNDING	4
38	951206	CARRIER	CVN	FATALITY	MAINTENANCE	8
39	960125	COMBATANT	FFG	EQPT DAMAGE	GROUNDING	9
40	960215	CARRIER	CV	FATALITY	MOB	5
41	960306	CARRIER	CV	FATALITY	GENERAL	6
42	960401	AUXILIARY	AOE	FATALITY	GENERAL	1
43	960517	COMBATANT	SSN	EQPT DAMAGE	COLLISION	9
44	961014	CARRIER	CVN	EQPT DAMAGE	COLLISION	38
45	961107	AUXILIARY	AOE	FATALITY	GENERAL	6
46	961112	COMBATANT	DDG	EQPT DAMAGE	GROUNDING	38

APPENDIX C. TEN-YEAR MISHAP FREQUENCY DATA

Calendar Year	Quarter	Cumulative Quarter	# Mishaps	# Ships	Mishap Rate
1987	1	1	5	530	0.009
	2	2	5	531	0.009
	3	3	14	532	0.026
	4	4	1	539	0.002
1988	1	5	6	538	0.011
	2	6	2	540	0.004
	3	7	7	541	0.013
	4	8	3	536	0.006
1989	1	9	3	535	0.006
	2	10	13	534	0.024
	3	11	3	528	0.006
	4	12	10	527	0.019
1990	1	13	1	521	0.002
	2	14	6	514	0.012
	3	15	5	513	0.010
	4	16	5	512	0.010
1991	1	17	5	505	0.010
	2	18	5	507	0.010
	3	19	7	507	0.014
	4	20	3	492	0.006
1992	1	21	5	475	0.011
	2	22	3	466	0.006
	3	23	3	458	0.007
	4	24	4	453	0.009
1993	1	25	3	465	0.006
	2	26	3	463	0.006
	3	27	1	457	0.002
	4	28	3	447	0.007
1994	1	29	4	423	0.009
	2	30	1	400	0.003
	3	31	2	400	0.005
	4	32	4	396	0.010
1995	1	33	3	382	0.008
	2	34	5	371	0.013
	3	35	2	369	0.005
	4	36	2	370	0.005
1996	1	37	4	369	0.011
	2	38	3	371	0.008
	3	39	0	372	0.000
	4	40	4	374	0.011

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